Exploiting the directional sensitivity of the Double Chooz near detector

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In scintillator detectors, the forward displacement of the neutron in the reaction $\bar{\nu}_e + p \to e^+ + n$ provides neutrino directional information as demonstrated by the CHOOZ reactor experiment with 2,500 events. The near detector of the forthcoming Double Chooz experiment will collect 1.6×10^5 events per year, enough to determine the average neutrino direction with a 1σ half-cone aperture of $2.3°$ in one year. It is more difficult to separate the two Chooz reactors that are viewed at a separation angle $\phi = 30°$. If their strengths are known and approximately equal, the azimuthal location of each reactor is obtained with $\pm 6°$ (1σ) and the probability of confusing them with a single source is less than 11%. Five year's data reduce this "confusion probability" to less than 0.3%, i.e., a 3σ separation is possible. All of these numbers improve rapidly with increasing angular separation of the sources. For a setup with $\phi = 90°$ and one year's data, the azimuthal 1σ uncertainty for each source decreases to $\pm 3.2°$. Of course, for Double Chooz the two reactor locations are known, allowing one instead to measure their individual one-year integrated power output to $\pm 11\%$ (1σ), and their five-year integrated output to $\pm 4.8\%$ (1σ).

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I. INTRODUCTION

The search for the neutrino mixing angle θ_{13} has led to a number of proposals for reactor neutrino experiments, where anti-neutrinos are registered in liquid scintillator detectors by the inverse β decay

$$\bar{\nu}_e + p \to e^+ + n \,. \tag{1}$$

In this reaction the neutron is scattered preferentially in the forward direction so that it retains some memory of the neutrino's initial direction, an effect first observed in experiments at the Gösgen reactor complex [1]. By reconstructing the vertices of the positron and neutron absorptions, one obtains an image of the neutrino source.

The CHOOZ experiment demonstrated the feasibility of this approach in that 2,500 events were enough to locate the source within a 1σ half-cone aperture of $18°$ [2, 3]. In principle, this method also allows one to determine the location of a galactic supernova explosion [2, 3] and the distribution of anti-neutrinos emitted by the natural radioactive elements in the Earth [4, 5], although in practice these applications are severely limited by the relatively small number of events.

Here we investigate the potential of future reactor experiments to exploit the same effect, but with much larger statistics. In particular, the upcoming Double Chooz experiment [6] will be a first important test of the principles of directional measurements, which will explore the requirements for future large volume detectors. Double

Chooz will operate two nearly identical detectors at distances of roughly 280 m and 1,050 m, respectively. The near detector will register 1.6×10^5 events per year, vastly exceeding the exposure of the CHOOZ experiment that was located at the far site of Double Chooz and had only a short data-taking period. Thus one year of Double Chooz data correspond to 64 times the CHOOZ exposure and hence to an 8-fold improved angular resolution, implying that the neutrino source can be located within a 1σ half-cone aperture of $2.3°$.

The Chooz nuclear power plant consists of two reactors that are viewed by the near detector at an angular separation $\phi = 30°$ so that one may well wonder if it is possible to separate the "neutrino images" of the two sources and/or to monitor their individual neutrino and thus power output. In spite of the impressive single-source directional sensitivity, this is not entirely obvious or trivial. Even though the average neutrino direction can be determined very well, separating two very blurred neutrino images is not simple even with the large event rate at the Double Chooz near detector.

In Sec. II we outline the Double Chooz experiment and specify our simplifying assumptions where we use the previous CHOOZ detector properties as our benchmark. In Sec. III we provide simple analytic estimates before turning in Sec. IV to a detailed Monte Carlo analysis of the Double Chooz setup and a hypothetical setup with a larger separation angle that could be of relevance to future experiments. We conclude in Sec. V.

II. EXPERIMENTAL SETUP

Both Double Chooz detectors will consist of about 10 tons of Gadolinium-loaded scintillator, with a Gd concentration of 0.1%. The final-state neutron of reaction

Eq. (1) is captured by a Gd nucleus with an efficiency of 90%, releasing 2–3 γ rays with a total energy of about 8 MeV. The directional sensitivity of such detectors rely on the forward displacement of the final-state neutron in Eq. (1) relative to the location of the final-state positron annihilation. Taking into account scattering and thermalization, an average displacement $\ell = 1.7$ cm with an rms uncertainty of approximately 2.4 cm for the x-, y- and z-directions was calculated [7]. Experimentally, the CHOOZ experiment found $\ell = 1.9 \pm 0.4$ cm [2]. To be specific we will use

$$\ell = 1.9 \text{ cm}, \tag{2}$$

representing an average over the incoming neutrino energies and the outgoing neutron directions. The large spatial distribution of the neutron absorption points as well as the even larger uncertainty of the neutron and positron event reconstruction imply that indeed only the average of the neutron displacement matters here.

The experimental output used for the directional information is a set of reconstructed displacement vectors $\mathbf{r}_i$ between the positron-annihilation and neutron-capture events, where $i = 1, \ldots, N$. In the Double Chooz near detector we have in one year

$$N = 1.6 \times 10^5 \tag{3}$$

events, originating from both reactor cores together. Unless otherwise stated we will always use this event number in our numerical estimates.

Our main simplifying assumption is that for a single neutrino source the distribution of the displacement vectors is a Gaussian with equal width L in each direction. In the first CHOOZ paper addressing the neutrino imaging of a reactor [2], an rms uncertainty for the neutron event reconstruction of 17–17.5 cm was given in their Fig. 2. Their Fig. 3 implies $L = 19$–20 cm and thus a positron event reconstruction uncertainty of 8–10 cm, in agreement with a similar result of the Borexino collaboration [8]. In a later CHOOZ publication [3], the rms uncertainty for the neutron event reconstruction was given as 19 cm. Assuming 9 cm for the average positron reconstruction uncertainty leads to

$$L = 21 \text{ cm} \tag{4}$$

that we will use as our benchmark value. With the planned photomultiplier coverage in Double Chooz one does not expect to improve on this value [9] so that the CHOOZ characteristics provide a realistic estimate.

Given a Gaussian distribution of width L, its center of gravity can be determined with a 1σ precision $L/\sqrt{N}$. Therefore, the 1σ uncertainty for the angular location of a single source is $(L/\ell)/\sqrt{N}$ that applies separately to the azimuthal and zenith angle. One year's data provide an angular uncertainty of $\pm 1.58°$. If both the azimuthal and zenith angle are not known, the corresponding 1σ half-cone aperture for the source location is $2.4°$. Scaling this to 2,500 events leads to $19.2°$, corresponding reasonably well to the CHOOZ value of $18°$ [2].

We will investigate a situation with two reactors that, together with the detector, define the x-y-plane of our coordinate system. The y-axis is taken to point from the detector towards the reactors (Fig. 1). The detector views the reactors with azimuthal angles ϕ_1 and ϕ_2 relative to the y-direction. We have chosen ϕ_1 to have a positive and ϕ_2 a negative sense of rotation. The common zenith angle θ of both reactors is measured against the x-y-plane. We use $\theta = 0°$ for the true reactor locations, but in general θ can be a fit parameter (Sec. IV D).
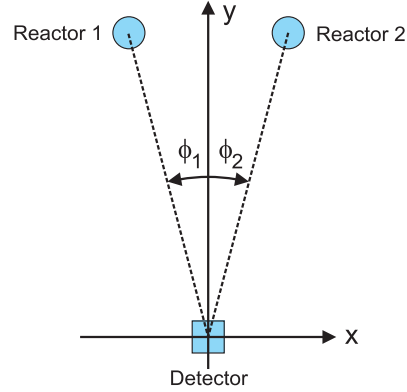

FIG. 1: Geometric setup.

With this geometric setup, the two reactor sources produce a normalized distribution of positron-neutron displacement vectors $\mathbf{r} = (x, y, z)$ of

$$f(\mathbf{r}) = \frac{1}{(2\pi)^{3/2} L^3} \exp\left[-\frac{(z + \ell \sin\theta)^2}{2L^2}\right] \sum_{i=1}^{2} b_i \exp\left[-\frac{(x + \ell \cos\theta \sin\phi_i)^2 + (y + \ell \cos\theta \cos\phi_i)^2}{2L^2}\right]. \tag{5}$$

Here, b_i with $b_1 + b_2 = 1$ represent the individual reactor contributions to the total event number N. Moreover, we define the separation angle $\phi = |\phi_1 - \phi_2|$ and the average

of the neutrino direction

$$\phi_c = b_1 \phi_1 + b_2 \phi_2. \tag{6}$$

III. ANALYTIC ESTIMATES

A. Width L of displacement-vector distribution

The width L of the distribution of the reconstructed positron-neutron displacement vectors $\mathbf{r}$ can be determined from the Double Chooz experiment itself. Assuming that the detector response is spherically symmetric, one can extract L from the z-distribution $f_z(z)$ of the displacement vectors. This distribution is equivalent to that from a single source. The distribution of L for many realizations, each with $N \gg 1$, is essentially Gaussian with

$$\frac{\sigma_L}{L} = \frac{1}{\sqrt{2N}}\,. \tag{7}$$

One year's data provide L with a fractional precision of 1.7×10^{-3} so that its uncertainty is negligible for our further discussion. In addition, one could test deviations from the assumed Gaussianity of the distribution.

B. Average neutron displacement ℓ

The average neutron forward displacement ℓ can be extracted from the y-distribution of the displacement vectors. Assuming a symmetric setup with $\phi_1 = -\phi_2 = \beta$, $f(\mathbf{r})$ factorizes as $f_x(x)f_y(y)f_z(z)$ and $f_y(y)$ is independent of the relative reactor strengths. The average and variance are $\bar{y} = \ell \cos \beta$ and $\langle y^2 - \bar{y}^2 \rangle = L^2$ so that

$$\begin{aligned}
\ell &= \frac{\bar{y}}{\cos \beta}\,, \\
\frac{\sigma_\ell}{\ell} &= \frac{L}{\ell}\frac{1}{\cos \beta \sqrt{N}}\,.
\end{aligned} \tag{8}$$

In Double Chooz we have $\phi = 2\beta = 30°$ or $\cos \beta = 0.966$. For the purpose of determining ℓ, the two reactors almost act as a single source even at the near detector. After one year the $1\,\sigma$ uncertainty will be $\pm 2.9\%$. Scaled to 2,500 events, this forecast corresponds reasonably well to the ℓ uncertainty of $\pm 20\%$ found by CHOOZ.

C. Relative reactor strength

As a first nontrivial application we address the question of how well one can monitor the relative reactor strengths. With $\phi_1 = -\phi_2 = \beta$, only the x-distribution carries information on b_1 and b_2, and in particular

$$\begin{aligned}
\bar{x} &= (b_1 - b_2)\,\ell \sin \beta\,, \\
\langle x^2 - \bar{x}^2 \rangle &= L^2 + [(1 - (b_1 - b_2)^2]\,(\ell \sin \beta)^2\,.
\end{aligned} \tag{9}$$

The variance is very close to L^2 because $L \gg \ell$ so that

$$\begin{aligned}
b &= \frac{1}{2}\left(1 + \frac{\bar{x}}{\ell \sin \beta}\right)\,, \\
\sigma_b &= \frac{L}{\ell}\frac{1}{2 \sin \beta \sqrt{N}}\,,
\end{aligned} \tag{10}$$

where

$$b = b_1 = 1 - b_2\,. \tag{11}$$

With $\sin \beta = 0.259$ we have after one year $\sigma_b = 0.053$. With $b = 0.5$ the $1\,\sigma$ uncertainty of each individual reactor strength is $\pm 10.7\%$, whereas the uncertainty of their sum is only $\pm 0.25\%$.

D. Separation angle of reactors

We have seen that for the Double Chooz setup, the directional sensitivity of the near detector allows one to determine the integrated source strength of the two reactors separately, even though the uncertainty remains relatively large for one year of data. We now ask the opposite question if one can separate the "neutrino images" of the two reactor cores, assuming their relative strength is known, and assuming the detector characteristics L and ℓ have been established by other means precisely enough that their uncertainty does not matter in the following.

We primarily discuss how well the separation angle $\phi = |\phi_1 - \phi_2|$ can be determined, assuming we know that there are exactly two sources in the x-y-plane that produce equal numbers of events. The obvious observables are the central coordinates $\bar{x}$, $\bar{y}$, and $\bar{z}$ of the displacement vector distribution and their variances.

At first one may think that the width of the observed distribution $f(\mathbf{r})$ is broadened in the x-direction if one has two sources because this distribution is a superposition of two Gaussian distributions of width L that are displaced relative to each other by the distance $2\ell \sin \beta$ where we have assumed $\phi_1 = -\phi_2 = \beta$. However, one easily finds in this case

$$\langle x^2 - \bar{x}^2 \rangle = L^2 + \ell^2 \sin^2 \beta\,. \tag{12}$$

The rms width of the x-distribution increases only quadratically in a small quantity with respect to the width L of a single source. For our parameters, the rms width of the double Gauss function is the same as that of a single Gaussian within 3×10^{-4} and thus indistinguishable, even with five year's data of almost a million events. Analogous conclusions pertain to the higher moments of a single Gaussian compared to a double Gauss function when their separation is much smaller than their width. In other words, with the foreseen statistics of the Double Chooz near detector, the neutrino images of the two reactors are far too blurred to be separated.

However, it is still possible to distinguish a single source from two sources if one takes advantage of the information encoded in the average coordinates of the displacement vector distribution. In the symmetric setup assumed here, information about the separation angle is provided by the distribution f_y that we have already used in Sec. III B to determine ℓ if the separation angle

is known. Turning this argument around we may instead solve for $\cos\beta$. Its uncertainty is

$$\sigma_{\cos\beta} = \frac{L}{\ell\sqrt{N}}\,, \qquad (13)$$

which is 2.8×10^{-2} for our usual parameters and one year's data. If the separation angle is large, it can be ascertained with fairly good accuracy. On the other hand, for the Double Chooz geometry with $\cos\beta = 0.966$, the reactors could be barely separated on this basis, even with five year's data. Moreover, since the angular separation relies on a measurement of the quantity $\ell\cos\beta$, an independent precise determination of ℓ is necessary.

In a certain number of cases the value for $\cos\beta$ implied by the data will exceed unity and will thus be unphysical. In other words, in these cases one cannot distinguish a single source from two sources. Since $\cos\beta$ follows a Gaussian distribution and using the width Eq. (13), this will be the case with the "confusion probability"

$$p_{\text{confusion}} = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\cos\beta - 1}{\sqrt{2}\,\sigma_{\cos\beta}}\right)\right]\,. \qquad (14)$$

For our usual parameters and one year's data we have $p_{\text{confusion}} = 10.9\%$. After five years this number reduces to 0.29%. Turning this around, in more than 99.7% of all cases the data will imply the presence of two sources. Therefore, we estimate that the Double Chooz near detector takes five years to distinguish the two reactors from a single source with a $3\,\sigma$ confidence.

The reason for this relatively poor performance is that even for a separation angle as large as $\phi = 30°$, the relevant quantity $\cos(\phi/2) = 0.966$ is difficult to distinguish from 1 for the given statistics. On the other hand, if the separation angle is somewhat larger, the deviation of $\cos(\phi/2)$ from 1 itself quickly becomes of order unity so that $\cos(\phi/2)$ can be easily distinguished from 1. Assuming the same detector characteristics and $\phi = 90°$, we estimate that one could measure ϕ with a precision of a few degrees even after only one year.

On the other hand, determining the central angle ϕ_c becomes more difficult if the separation angle is too large. For two equally strong reactors on opposite sides of the detector ($\phi = 180°$), the separation angle can be very well measured, whereas ϕ_c would remain completely undetermined. One would conclude that there are two reactors at opposite sides without any information on their absolute direction.

IV. MAXIMUM-LIKELIHOOD ESTIMATE

A. The method of maximum likelihood

The analytic estimates of the previous section are based on simple properties of the displacement-vectors distribution, notably the coordinates of its center of gravity. Moreover, we have argued that the shape of the double-Gauss distribution Eq. (5) is very similar to that of a single Gaussian. Therefore, even for a five year exposure at the Double Chooz near detector, the shape of the displacement-vector distribution holds little additional information. Still, the maximum information can be extracted by performing a maximum-likelihood analysis, i.e., by fitting the measured distribution of displacement vectors to a function of the form Eq. (5).

The likelihood function of a set of N independently measured displacement vectors $\mathbf{r}_i = (x_i, y_i, z_i)$ is

$$L(\alpha) = \prod_{i=1}^{N} f(\mathbf{r}_i; \alpha)\,, \qquad (15)$$

with $f(\mathbf{r}_i; \alpha)$ given here by Eq. (5), where α denotes the a priori unknown parameters b_1, b_2, ϕ_1, and ϕ_2. The set of parameters that maximizes the likelihood returns the best-fit points of a given data set. The maximum likelihood analysis is the most powerful analysis method for unbinned data. Therefore, it is useful to compare the analytic results of the previous section with the maximum-likelihood method applied to sets of Monte Carlo data.

B. Relative reactor strength

As a first example we return to the task of determining the relative reactor strength. We assume that $\theta = 0°$ and $\phi_1 = -\phi_2 = 15°$ is known. Under these circumstances the distribution function factorizes and we will only keep $f_x(x)$ where we use $b_1 = b_2 = 0.5$ to generate Monte Carlo data sets for x with $N = 1.6\times10^5$ events (one year). For each realization we reconstruct b by a maximum-likelihood fit. In Fig. 2 we show the distribution of best-fit values from 1,000 runs together with a Gaussian distribution centered at $b = 0.5$ and a width
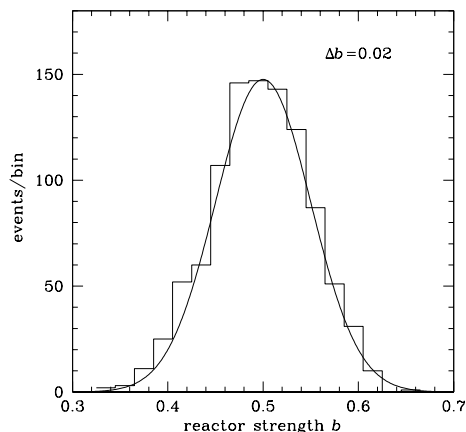

FIG. 2: Distribution of best-fit values of the reactor strength b for 1,000 Monte Carlo realizations, assuming our usual parameters and 1 year of data. The bin width is $\Delta b = 0.02$. We also show a Gaussian of width $\sigma_b = 0.053$, representing the analytic estimate of Eq. (10).

$\sigma_b = 0.053$ given by the analytic estimate Eq. (10). Both results correspond very well to each other.
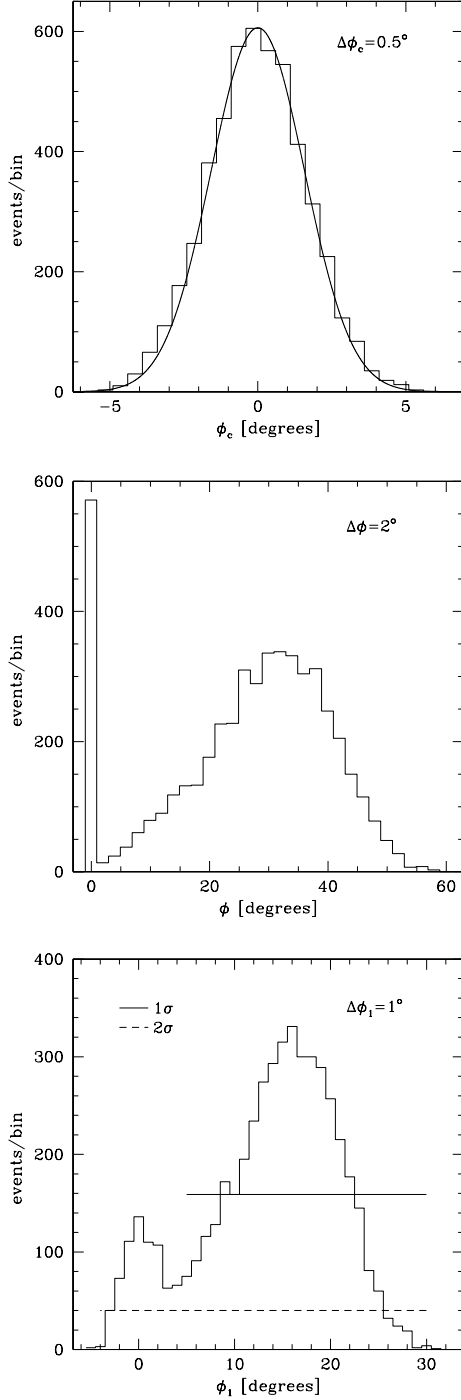

FIG. 3: Best-fit central angles $\phi_c = \phi_1 + \phi_2$ (*top*), separation angles $\phi = |\phi_1 - \phi_2|$ (*middle*), and azimuthal reactor location ϕ_1 (*bottom*) for 5,000 Monte Carlo realizations of our fiducial setup with 1.6×10^5 events (one year). The different bin widths are indicated in each panel. In the top panel we also show a Gaussian with the expected width of $1.6°$. In the bottom panel, the horizontal solid line indicates the interval containing 68% of all values, the dashed line 95.4%.

C. Reactor directions

As a next case we assume that the reactor strengths are known to be $b_1 = b_2 = 0.5$ and that the zenith angle for both sources is $\theta = 0°$, whereas the azimuthal reactor locations ϕ_1 and ϕ_2 are our fit parameters. Since the z-distribution factors out, we generate Monte Carlo data sets consisting of $N = 1.6 \times 10^5$ two-dimensional displacement vectors (x, y). For 5,000 Monte Carlo realizations we show the distribution of reconstructed best-fit central angles $\phi_c = b_1\phi_1 + b_2\phi_2$ in the top panel of Fig. 3 together with a Gaussian of width $1.6°$ that corresponds to the expected analytic width. Both results agree well with each other.

In the middle panel of Fig. 3 we show the corresponding distribution of best-fit separation angles $\phi = |\phi_1 - \phi_2|$ which is taken to be a positive number because the reactors have equal strength and thus are not distinguishable. The distribution consists of a continuous component and a spike at $\phi = 0°$. This solution corresponds to those cases where the data prefer a single source as discussed in Sec. III D. According to Eq. (14) this confusion should
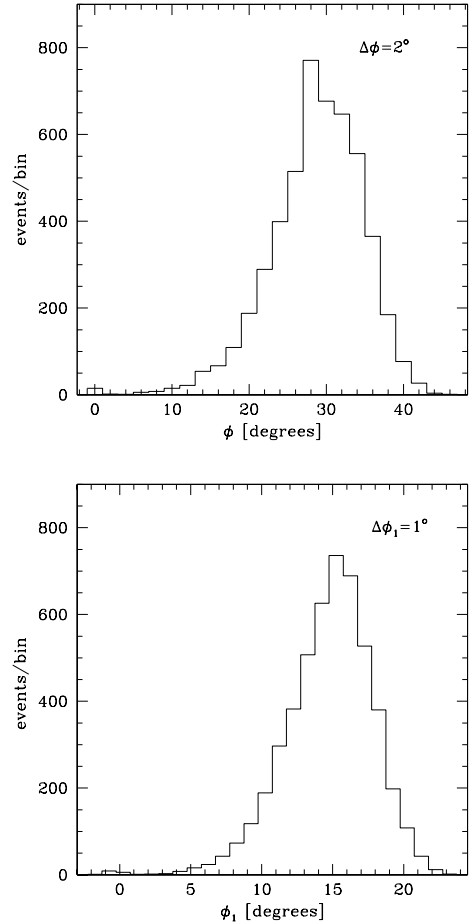

FIG. 4: Best-fit separation angles ϕ (*top*) and reactor locations ϕ_1 (*bottom*) as in Fig. 3, here for $N = 8 \times 10^6$ (five years).

arise in 10.9% of all cases, in good agreement with the size of the spike in Fig. 3 if we recall that the sum over all bins represents 5,000 Monte Carlo realizations.

Finally we show in the bottom panel of Fig. 3 the distribution of the reconstructed azimuthal reactor location ϕ_1. Since the two reactors are taken to have equal strength, they are not distinguishable so that the distribution for $-\phi_2$ is the same. The distribution is bimodal with one peak at the true location of $\phi_1 = 15°$ and another at the central angle $\phi_c = 0°$, corresponding to those cases where the two reactors cannot be distinguished from a single source. The width of this peak roughly corresponds to the width of the central-angle distribution in the top panel. We have also indicated where 68% (solid line) and 95% (dashed line) of all values fall around the best-fit value. Even though the distributions are not Gaussian, we refer to these regions as 1σ, 2σ etc. intervals. The 1σ interval is approximately $12°$ wide, whereas the 2σ interval includes the secondary peak at $0°$. As the number of events increases, the ϕ_1 distribution approaches a Gaussian and the peak at $0°$ decreases. It takes roughly seven years of data to exclude this secondary peak from the 3σ confidence region.

In Fig. 4 we show the distribution of separation angles ϕ and of reactor locations ϕ_1 for 5,000 Monte Carlo realizations, each with 5 years of data ($N = 8 \times 10^5$). The spike at $0°$ of the separation-angle distribution has indeed decreased below 0.3%, confirming our earlier analytic estimate that with five year's data a 3σ separation of the Double Chooz reactors is possible. Note, however, that the peak around $0°$ of the ϕ_1 distribution remains in the 3σ region.

As a more optimistic case, we consider a hypothetical setup with a separation angle $\phi = 90°$. The distributions of the reconstructed angles are essentially Gaussian in the relevant region around the best-fit values. With $N = 1.6 \times 10^5$, corresponding to 1 year at Double Chooz, the 1σ uncertainty for ϕ_1 is $\pm 3.2°$, for the central angle ϕ_c

it is $\pm 2.3°$ and for the separation angle ϕ it is $\pm 4.6°$. We illustrate this case in Fig. 5 where we show the likelihood contours for ϕ and ϕ_c corresponding to 1, 2, and 3σ confidence regions. Note that the uncertainty of ϕ is twice that of ϕ_c and that of ϕ_c is worse than it was for a smaller separation angle.

D. Reactor directions with tilt

As a final example we include the zenith angle θ as a fit parameter. In other words, we generate Monte Carlo data sets for the full distribution function Eq. (5) consisting of $N = 1.6 \times 10^5$ displacement vectors. As a first case we show in Fig. 6 likelihood contours for ϕ_1 and θ when there is a single source and the data are analyzed with the prior assumption that indeed there is only a single source, i.e., assuming $phi_1 = 0°$, $b_1 = 1$ and $b_2 = 0$. This figure can be taken as a false-color neutrino image of a single reactor and illustrates the single-source imaging power of the near detector at Double Chooz. The solid lines correspond to the 1, 2 and 3σ contours.

Next we generate Monte Carlo realizations based on two sources with separation angles $30°$, $70°$, and $90°$,

FIG. 6: Likelihood contours of ϕ_1 and θ corresponding to 1, 2 and 3σ confidence regions for a single reactor source. This figure is based on one Monte Carlo realization with $N = 1.6 \times 10^5$ events.
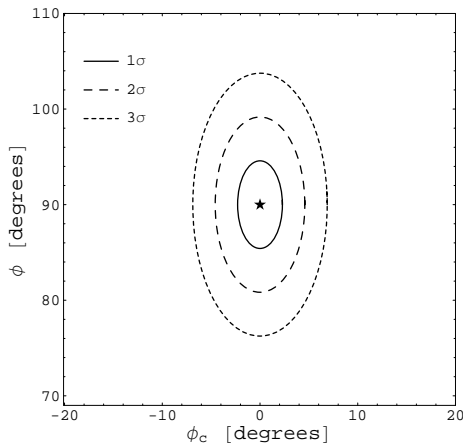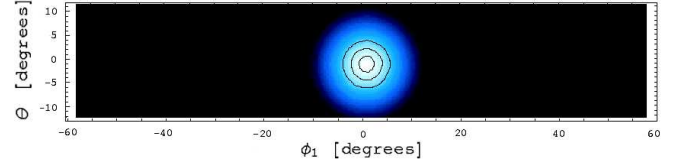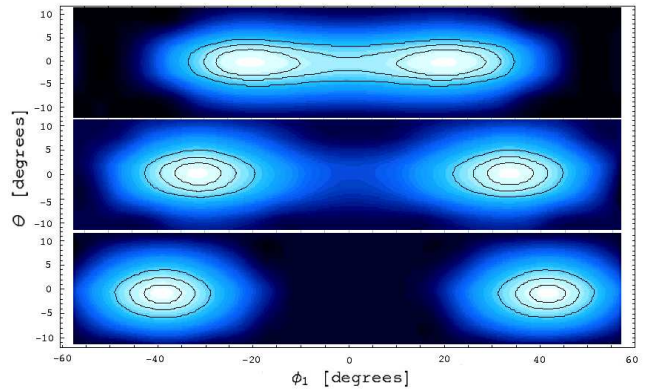

FIG. 5: Likelihood contours of ϕ and ϕ_c for one Monte Carlo realization with $N = 1.6 \times 10^5$ events generated from a setup with separation angle $\phi = 90°$ and central angle $\phi_c = 0°$.

FIG. 7: Likelihood contours projected onto the ϕ_1-θ plane, where the solid lines correspond to the 1, 2 and 3σ confidence regions. From top to bottom the true separation angle was $30°$, $70°$, and $90°$, respectively. Each panel shows a "typical" Monte Carlo realization consisting of $N = 1.6 \times 10^5$ events.

respectively. The fit parameters of the maximum likelihood analysis are θ, ϕ_1, and ϕ_2, where both ϕ_1 and ϕ_2 can a priori vary in the entire interval from $-180°$ to $+180°$. In Fig. 7 we show likelihood contours for three "typical" Monte Carlo realizations projected onto the ϕ_1-θ plane. In our case of equal reactor strengths, $L(\theta, \phi_1, \phi_2) = L(\theta, \phi_2, \phi_1)$ so that the corresponding plot for ϕ_2 is identical.

The panels of Fig. 7 can be taken as false-color neutrino images of two reactors, although this interpretation must be used with care because we show the likely location of one of the reactors, not really the "images" of two neutrino sources.

For small separation angles, where the two "reactor images" merge, the interpretation of the shown contours as 1, 2 and 3σ confidence regions is only approximate. We also note that the distribution of zenith angles θ, after marginalizing over the azimuthal angles, is the same in all cases of Figs. 6 and 7 within statistical fluctuations.

V. CONCLUSIONS

We have investigated the "neutrino imaging power" of the Double Chooz near detector that will collect as many as 1.6×10^5 events per year. Its angular sensitivity is based on the average forward displacement of the neutron in the inverse-beta detection reaction. For realistic assumptions derived from the properties of the previous CHOOZ experiment, the width of the distribution of reconstructed displacement vectors is about ten times larger than the displacement itself, leading to an extremely blurred neutrino image of a reactor.

For a single source, this image can be sharpened with enough statistics so that its direction can be determined with very good precision. At Double Chooz we obtain the average neutrino direction with a 1σ half-cone aperture of $2.4°$ with one year of data.

However, with the given statistics, the images of two or more sources merge completely in the sense that the shape of the displacement-vector distribution is indistinguishable from that of a single source. Yet the average of all measured displacement vectors still contains nontrivial information on the source directions. It is very difficult to separate two sources if their angular distance ϕ is so small that $1 - \cos(\phi/2) \ll 1$. Thus for Double Chooz we find that the setup is ineffectual for a clear separation of the reactors. After 5 years of Double Chooz, the reactors can be separated at the 3σ level.

With increasing separation angle it becomes much easier to distinguish the reactors. For a setup with $\phi = 90°$, even one year's data would be enough to measure the separation angle to about $\pm 10°$ at 3σ.

For Double Chooz, the location of the reactors is perfectly known, of course. In this case one can use the angular sensitivity to determine the two reactor strengths from the neutrino signal alone and one can determine the detector response characteristics L and ℓ from the same data. At 1σ, the one-year integrated power of one of the reactors can be determined to $\pm 11\%$, the five-year integrated value to $\pm 4.8\%$. The total event rate over these periods is determined within $\pm 0.25\%$ and $\pm 0.11\%$, respectively.

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